Transportation Research Part F 78 (2021) 446–465

Contents lists available at ScienceDirect

Transportation Research Part F

journal homepage: www.elsevier.com/locate/trf

Should older people be considered a homogeneous group when interacting with level 3 automated vehicles?

Shuo Li [a,*], Phil Blythe [a], Yanghanzi Zhang [a], Simon Edwards [a], Jin Xing [a], Weihong Guo [a], Yanjie Ji [b], Paul Goodman [a], Anil Namdeo [c]

[a] School of Engineering, Newcastle University, Cassie Building, Claremont Road, Newcastle upon Tyne NE1 7RU, UK
[b] Jiangsu Key Laboratory of Urban ITS, Jiangsu Province Collaborative Innovation Centre of Modern Urban Traffic Technologies, School of Transportation, Southeast University, Southeast University Road 2, Nanjing 211189, China
[c] Department of Geography and Environmental Sciences, Northumbria University, Ellison Place, Newcastle upon Tyne NE1 8ST, UK

ARTICLE INFO

Article history:
Received 28 August 2020
Received in revised form 21 February 2021
Accepted 8 March 2021

Keywords:
Level 3 automated vehicle
Highly automated vehicles
Vehicle automation
Older drivers
Older people
Human factors
Takeover control
User requirements
Driving simulator

ABSTRACT

Exploring the future mobility of older people is imperative for maintaining wellbeing and quality of life in an ageing society. The forthcoming level 3 automated vehicle may potentially benefit older people. In a level 3 automated vehicle, the driver can be completely disengaged from driving while, under some circumstances, being expected to take over the control occasionally. Existing research into older people and level 3 automated vehicles considers older people to be a homogeneous group, but it is not clear if different subgroups of old people have different performance and perceptions when interacting with automated vehicles. To fill this research gap, a driving simulator investigation was conducted. We adopted a between-subjects experimental design with subgroup of old age as the independent variable. The differences in performance, behaviour, and perception towards level 3 automated vehicles between the younger old group (60–69 years old) and older old group (70 years old and over) was investigated. 15 subjects from the younger old group (mean age = 64.87 years, SD = 3.46 years) and 24 from the older old group (mean age = 75.13 years, SD = 3.35 years) participated in the study. The findings indicate that older people should not be regarded as a homogeneous group when interacting with automated vehicle. Compared to the younger old people, the older old people took over the control of the vehicle more slowly, and their takeover was less stable and more critical. However, both groups exhibited positive perceptions towards level 3 automation, and the of older old people's perceptions were significantly more positive. This study demonstrated the importance of recognising older people as a heterogeneous group in terms of their performance, capabilities, needs and requirements when interacting with automated vehicles. This may have implications in the design of such systems and also understanding the market for autonomous mobility.

1. Introduction

The world's population is ageing. The global population of older people aged 60 and above was 962 million in 2017, which was 2.5 times as large as that in 1980 (382 million). By 2050, the figure is predicted to double to approximately 2.1 billion,

* Corresponding author.
E-mail address: shuo.li@newcastle.ac.uk (S. Li).

https://doi.org/10.1016/j.trf.2021.03.004
1369-8478/

accounting for about 22% of the world's population (UN, 2017). Compared with the global trend, the population in the UK is ageing at an even faster pace (Musselwhite and Scott, 2019; ONS, 2020). In 1955, 16.25% of the UK population was aged 60 and over. This had increased to around 20% in 1985 and further grew to about 23% in 2015 (ONS, 2014). By 2030, the number of people aged 60 and older will account for about 25% of the overall UK population (ONS, 2020). Driving is closely associated with older people's ability to maintain mobility, independence and wellbeing (Musselwhite, 2011; Emmerson et al., 2013; Li et al., 2019c; Musselwhite and Scott, 2019). In the UK, travelling by car has become the dominant mode of transport for older people. The percentage of trips by car among older people in the UK increased from 58% in 1998 to 69% in 2012, whereas the percentage of trips as a driver by older people has grown from 38% in 1998 to 49% in 2012 (DfT, 2017).

Driving is a complicated activity requiring smooth interaction and the coordination of a number of physical, sensory and cognitive functionalities on the part of the driver (Attebo et al., 1996; Karthaus and Falkenstein, 2016; Li et al., 2018). Although older drivers generally have greater driving experience, good driving skills, drive cautiously (McGwin Jr and Brown, 1999; Li et al., 2019c), a range of age-related functional impairments could negatively affect people's safe driving ability, including declines in sensory, cognitive and psychomotor functions as well as age-related fragility and frailty (Li et al., 2003; Ferreira et al., 2013; Karthaus and Falkenstein, 2016; Sun et al., 2018; Howcroft et al., 2019; Ledger et al., 2019).

To compensate for the negative effects of these age-related functional impairments on driving, many older adults are very cautious when driving (Li et al., 2019c) and a great number of them modify and regulate their driving behaviour so as to reduce or avoid exposure to certain situations that they believe are difficult or potentially dangerous for them, for example, driving in adverse weather conditions, driving at night, in busy traffic (Ball et al., 1998; Raitanen et al., 2003; Charlton et al., 2006; Siren and Meng, 2013; Bellet et al., 2018). Older drivers have different opinions towards the concept of adopting self-regulatory driving behaviour. Some older drivers have been found to be more likely to adopt self-regulatory driving behaviour compared to others. These include female older drivers, older old drivers aged 75 and over as well as older drivers who had been involved in car collisions, those with objectively determined visual and/or cognitive impairments, kidney disease, cataracts or high blood pressure (Ball et al., 1998; Lyman et al., 2001; Charlton et al., 2006). However, some older drivers do not support the idea of self-regulatory driving behaviour. Jette and Branch (1992) found that some older adults insisted on carrying on driving for as long as they could and reducing driving by adopting self-regulatory behaviour may not be a perfect and practical method to ensure safe driving among all older adults.

The ultimate level of self-regulatory behaviour is driving cessation. The most common reasons for driving cessation among older drivers are medical issues as well as lack of confidence and increased nervousness while driving (Persson, 1993). Driving cessation could lead to a substantial decline in older drivers' ability to travel anywhere at any time when they want and need to (Kostyniuk and Molnar, 2008; Eby and Molnar, 2012). Reducing driving and driving cessation could have negative impacts on older drivers' mobility, independence, freedom and wellbeing, and are highly associated with increased social isolation, symptoms of depression and reduced self-worth. Attention should be paid as a matter of urgency by the whole of society to the subject of driving cessation in order to support older drivers so that they can effectively and smoothly adapt to alternative transport modes to replace driving (Musselwhite, 2011).

Along with ageing trends in the global population, the development of vehicle automation systems could potentially have a positive impact in enhancing mobility, accessibility and social inclusion for older people (Milakis and van Wee, 2020). Vehicle automation systems can be classified into several levels based on different functionalities and capabilities (SAE, 2014). Among these, the Level 3 automation system is an important innovation where control of the vehicle can be shared between the automation system and human drivers (SAE, 2014; DfT, 2015). Vehicles equipped with level 3 automation systems are able to perform full dynamic driving control, including steering, accelerating and braking, as well as monitoring the driving environment. The driver must be present but is allowed to be completely disengaged from the driving task and can safely engage in other non-driving related tasks. However, there are situations which the level 3 automation systems will not be able to cope with, such as entering road-works area, or driving on a rural road without lane markings or without network connections (Li et al., 2019c; Louw et al., 2019; Zhang et al., 2019a; Zhang et al., 2019b). In such situations the level 3 automated vehicle will initiate a takeover request to the driver and provide a sufficient lead time for them to take over control of the vehicle. In order to ensure safety, the driver must successfully take over control of the vehicle within the lead time provided (SAE, 2014; DfT, 2015).

1.1. Older people and vehicle automation

Existing research about human interaction between the level 3 automated vehicles have reached a consensus that it is imperative to not only focus on general drivers but also pay attention to the capabilities, needs and requirements of the specific older driver cohort. The impact of age on people's interaction with, perception of and requirements towards vehicle automation systems has been well investigated by previous research. However, there is a consistent trend that existing research has treated older people as a homogeneous group when studying their interaction with the level 3 automated vehicle. The impact of age has been mainly investigated by comparing the performance and behaviour between an experimental group of older people aged 60 years and over with a baseline group of younger people aged under 60 years old. For example, Körber et al. (2016) carried out a driving simulator investigation with 36 younger drivers (mean age = 23.28 years) and 36 older drivers (mean = 66.67 years) to investigate the effect of age on takeover performance in a level 3 automated vehicle. Participants were asked to perform tasks of verbally answering twenty questions presented on a hands-free mobile phone. Although, no effect of age on takeover time was found, older drivers braked more frequently and harder, and left higher times-to-collision. It was suggested that older drivers were safer and more cautious when taking over control from the level 3 automated vehicle, which was deemed to be due to their greater driving experience. In addition, Clark and Feng (2017) conducted a driving simulator study with 35 participants aged between 17 and 81 years to study age differences in preferences for non-driving-related tasks (NDRTs) as well as takeover performance in a level 3 automated vehicle. Age differences were found in preferences for non-driving-related tasks during automated driving. Older drivers performed more cautious and stable takeovers than the younger drivers. In addition, Li et al. (2019b) found that older drivers exhibited slower reactions and decision making than younger drivers when reassuming control from a simulated level 3 automated vehicle. Wu et al. (2020) used the driving simulator to investigate the impact of performing NDRTs on driver drowsiness in level 3 automated vehicles with 12 younger (mean age = 24.6 years), 12 middle-aged (mean age = 43.9 years), and 12 older people (mean age = 64.3 years). The latter were found to be affected differently by NDRTs compared to younger people, where performing NDRT had no impact on older people's drowsiness but worsened their takeover performance. Peng and Iwaki (2020) conducted a driving simulator investigation exploring differences in driver behaviour when interacting with a level 3 automated vehicle between 27 younger drivers (mean age = 28.1 years) and 27 older drivers (mean age = 73.0 years), where a significant impact of age on driver's visual attention and takeover performance was found. Huang and Pitts (2020) studied the influence of age on the perception of takeover requests using different modalities and attention allocation during level 3 automated driving with 24 younger drivers (mean age = 21.9 years) and 24 older drivers (mean age = 71.7 years). They found that older people allocated their attention more to the road than the non-driving related secondary task compared with their younger counterparts.

1.2. Regarding older people as a homogeneous group.

The cut-off point of 60 years of age has been widely accepted in referring to older people (WHO, 2016; UN, 2017; ONS, 2018; WHO, 2018) and it has been widely adopted by existing research about older people and advanced driver-assistance systems (ADAS) and vehicle automation systems (Emmerson et al., 2013; Guo et al., 2013; Körber et al., 2016; Clark and Feng, 2017; Li et al., 2019d). However, individuals may have different functionalities and capabilities and therefore could experience different physical, mental and psychological conditions and thus have different needs for assistance when they age and become referred to as old people (Berk, 2018; Li et al., 2019c). It is important to recognise that older people are not a homogeneous group (Alsnih and Hensher, 2003; Schoene et al., 2013; Su and Bell, 2013; O'Hern et al., 2015). Fail to recognise that could potentially ignore the variation in the ageing process and the increased risks linked with continued ageing and thus resulting in inequality among older people from different subgroups (Alsnih and Hensher, 2003; Schoene et al., 2013; Li et al., 2019c). Previous evidence suggested that substantial variation in ageing process exists from the age of 70 years, resulting in more severe impairments and declines in such sensory, cognitive, and psychomotor functionalities among older people from an older sub-group. For example, visual sensory functions decline with age, and those aged 70 and over experience more significant reductions in the useful field of view compared with those aged 60 to 69 (Isler et al., 1997; Karthaus and Falkenstein, 2016). Older old people also experience higher rates of hearing loss; for example, as many as 70% of people aged 80 experience noticeable impairments in their hearing (Murman, 2015; Karthaus and Falkenstein, 2016). Older age would also lead to significant impairments in executive cognitive functionalities such as, decision making, problem solving, and reaction planning as well as multitasking, and age-related impairments in concept formation, abstraction and mental flexibility are particularly common among those aged 70 and over (Deaton and Parasuraman, 1993; Bigler, 2012; Murman, 2015). In addition, older old people tend to exhibit more significant declines in physical strength and functional fitness compared to younger old people. They are less physically active and less functionally flexible and have significantly higher rates of muscle-strength decline (Milanović et al., 2013). The above variation of functional impairments associated with increased age gradually reduce the skills required for safe driving among older people (Dulisse, 1997). Increased age was found to be negatively linked with the driving performance of older people (Lee et al., 2003). For those aged 70 and over, their road accident casualty rates are positively associated with age (Eberhard, 2008) and their risk of fatal injury is higher than that of those aged 60 and 69 (Regev et al., 2018). The main contributor to this is their increased fragility with age (Christopher, 2013). Moreover, older people aged over 70 also have a higher possibility to be responsible for a road accident (Eberhard, 2008; Young and Bunce, 2011). The potential implication of the 70 years of age on the driving performance has been recognised. In the UK, a car driving licence expires at the age of 70 years. After that, people need to renew their driving licences every three years if they want to continue driving (Christopher, 2013; DVLA, 2019).

1.3. Research gap

Existing research about older people and vehicle automation has mainly focused on exploring the effect of age by comparing the behaviour and performance of a cohort of older people which is assumed to be homogeneous and younger counterpart cohorts. A series of research has done by the current authors to compare the interaction with the level 3 automated vehicle between older people and younger counterpart under the impact of different weather (Li et al., 2018), performing different non-driving related tasks (Li et al., 2019b) as well as under the influence of different human–machine interfaces (Li et al., 2019d). Significant impact of age on performance of taking over control from the level 3 automated vehicle was observed. However, it is not clear if old people from different sub-groups of old age exhibit differences in performance, behave in different ways or have divergent perceptions when interacting with automated vehicles. The cut-off of 70 years of age has been adopted by a wide range of studies as an important threshold when referring to the older subgroup among older people (Forman et al., 1992; Morrison et al., 1997; Russell et al., 1999; Gallucci et al., 2009; Miller et al., 2016). Research is urgently needed to answer questions related to whether it is wise to consider older people as a homogeneous cohort in terms of travel and interacting with automated vehicles. A significant research gap remains in understanding whether tailored support and assistance may be needed for any specific sub-groups of older people. While harnessing the opportunities of automation to facilitate better health and quality of life in an ageing society, insufficient information and knowledge in this area could potentially result in the design of automated vehicles according to a 'one size fits all' approach, consequently ignoring the capabilities, needs and requirements of older people belonging to some specific sub-groups of old age. Such an outcome may potentially prevent the automated vehicle to become the future mobility for older people and thus fail to deliver the promise to fulfil the needs of a healthy ageing society.

1.4. Purpose of the research

To fill this gap in knowledge, this research details a driving simulator study that is aimed to investigate the differences in performance, behaviour and perceptions when interacting with level 3 automated vehicles between older people from two sub-groups of old age: a younger old group (60 to 69 year-olds) and an older old group (70 years and over).

The primary research hypotheses of this study are that:

- Younger older people (aged 60 and lower) exhibit significantly more rapid takeover of the control as well as better takeover quality compared to the older old people (70 years and over).
- Younger older people have significantly different perception in terms of benefit and usefulness towards the level 3 automated vehicle compared to the older old people.

The first hypothesis is directional. It is derived from previous evidence that the decline in sensory, cognitive and psychomotor capabilities gradually deteriorate the skill needed for safe operation of a conventional vehicle manually (Dulisse, 1997) and driving performance of older people were found to be negatively correlated with increased (Lee et al., 2003). Therefore, it is important to explore whether this evidence is transferable in the context of interacting with the level 3 automated vehicle. The second hypothesis is non-directional. It is derived from the fact that 70 years is the threshold that older people's role as a driver starts to change-they either renew their driving license every three years or cease driving altogether (Christopher, 2013), thereby it would be worthy investigating how this may affect older people's perception of automated vehicle in terms of benefits and usefulness.

2. Methods

2.1. Participants

To be eligible to participate in the current study, two criteria are applied when recruiting subjects: firstly they should be aged 60 years and over; and secondly they should have valid UK driving licences and be an active driver at the time of participation in the study. They were recruited from a user group of older people (called VOICE) which is based in the National Innovation Centre for Ageing (NICA). This recruitment for participants was augmented by approaches to individuals in Newcastle upon Tyne. In total, 39 older people (mean age = 71.18 years, SD = 6.06 years; max = 81 years, min = 60 years; 16 female, 23 male) participated in the study. Among them, 15 were from the younger subgroup of old people (mean age = 64.87 years, SD = 3.46 years; max = 69 years, min = 60 years; 5 female, 10 male), and 24 were from the older subgroup of older people (mean age = 75.13 years, SD = 3.35 years; max = 81 years, min = 70 years; 11 female, 13 male).

2.2. Driving simulator

This investigation took place in the Newcastle University driving simulator laboratory. It was located at the main campus of Newcastle University and has been recently moved to the National Innovation Centre for Ageing (NICA). The driving simulator used in this study is a fixed-based ST Software Jentig50 driving simulator (Fig. 1). It provides the driver with an approximately 270 degrees high resolution field of view through five 50-inch Full HD 1080p LCD displays. It includes all of the controls of a real vehicle, including a dynamic force feedback steering wheel, accelerator pedal, brake pedal, clutch pedal, adjustable car seat and safety belt. The dashboard, rear-view mirror and side mirrors are projected on the displays. It is also equipped with a 5.1 surround sound system which enhances the fidelity of the driving experience. The control panel and user interface of the driving simulator is accessed through a separate display which enables researchers to operate and control the driving scenarios and monitor system status remotely without disturbing the participants while they are using the simulator.

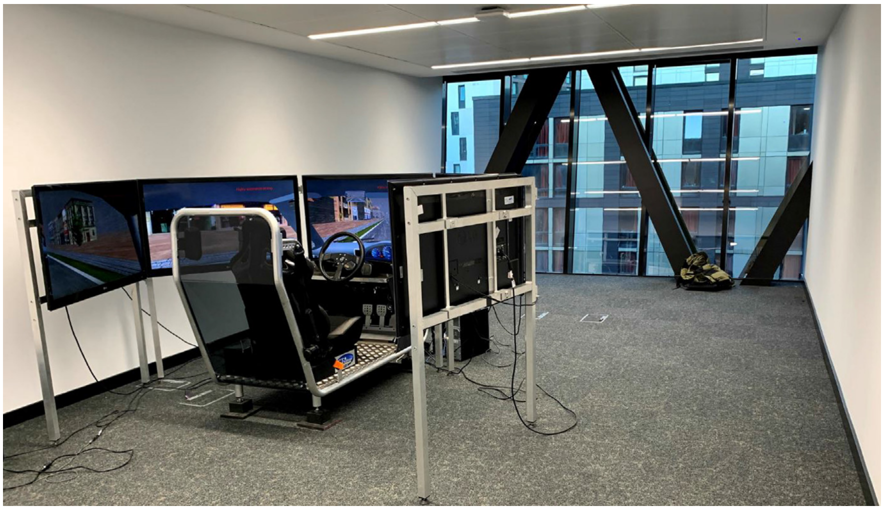

Fig. 1. Newcastle University fixed-based ST software Jentig50 driving simulator.

2.3. Level 3 automated vehicle scenario

The level 3 automated vehicle scenario adopted in this study incorporates a full takeover control situation which represents a complex and important human–machine interaction in level 3 automated vehicles (Gold et al., 2013a; Radlmayr et al., 2014; Gold et al., 2016; Li et al., 2019b). As Fig. 2 shows, the scenario starts with the driver turning on the engine and the automation system starting to perform longitudinal and lateral vehicle control and to accelerate the vehicle from 0mph to 30mph (13.41 m/s) when driving on the city road or to 60mph (26.82 m/s) on the motorway, the level 3 automation then maintain a constant speed of 30mph or 60mph in the centre of the left-hand lane of the dual carriageway for a duration of one minute. During this one minute of level 3 automated driving, the drivers are allowed to take their hands off the steering wheel, and their feet off the pedals, and to be completely disengaged from driving and encouraged to safely perform a

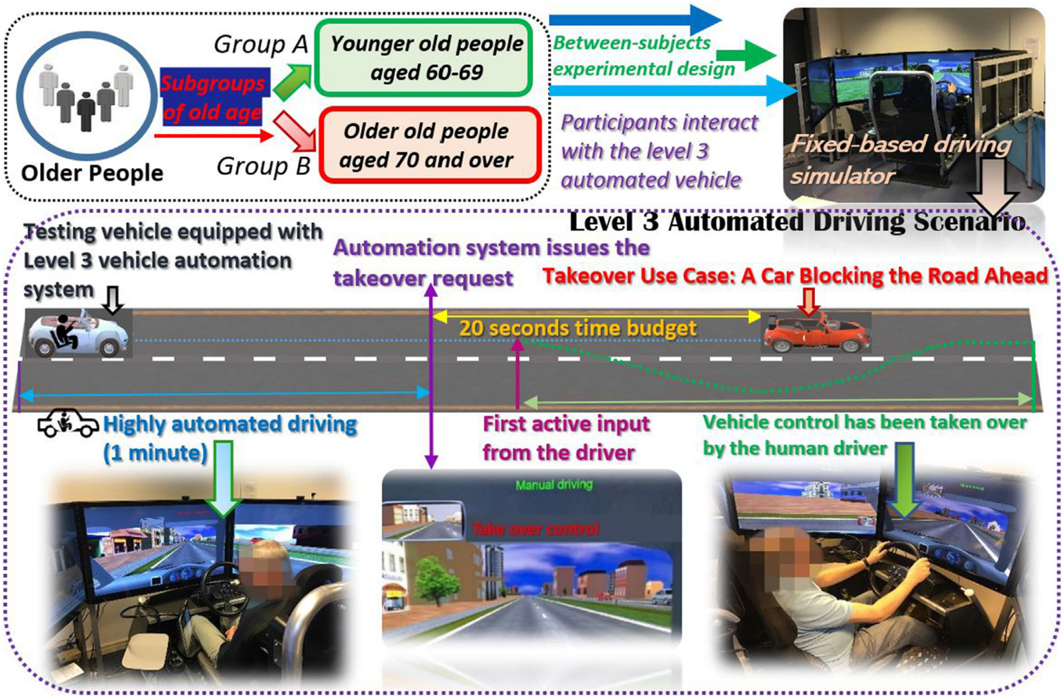

Fig. 2. Illustration of the experimental design and level 3 automated driving scenario.

mandatory reading task from a tablet mounted on the 45 degree left to the driving direction. After a duration of one minute, the system detects a stationary red vehicle blocking the driving lane ahead, and then it informs the driver of this using a visual and auditory takeover request (a red, large test, warning message is displayed on the screen "Take over control" and a computer-generated female voice saying "Attention, please take over the vehicle control"). Such a automation system-initiated takeover is demanding and complicated, which represents an important feature of level 3 automation vehicles (Flemisch et al., 2008; Gold et al., 2013a; Melcher et al., 2015; Lu et al., 2016). Meanwhile, the automation system continues to drive at its steady speed. On the urban road, the automated driving system detects the stationary car with an advance range of 268.20 m and informs the drivers with a lead time of 20 s. On the motorway, it detects the stationary car as a hazard at a range from the driver's car of 536.4 m and informs the drivers with a lead time of 20 s. The driver must reassume control of the vehicle within the 20 s before the automated vehicle reaches the stationary car. As long as the automation system detects active input from the driver (at least 2 degrees of steering wheel input and/or 10% of pressing the accelerator or brake pedals), it transfers control of the vehicle to the driver. Then, the driver needs to overtake the stationary car by conducting a lane change. This scenario has been widely used in previous studies of level 3 automated vehicles and has been proven to be effective in quantifying takeover performance (Gold et al., 2013a; Gold et al., 2016; Körber et al., 2016). After the driver has passed the stationary car, she/he is asked to pull over in the left-hand lane and the scenario ends.

2.4. Experimental design

Corresponding to the aim of the study, a simple between-subjects experimental design was implemented. As illustrated in Fig. 2, the between-subjects independent variable is subgroup of old age. It consists of two levels: younger old group aged 60–69 and older old group aged 70 and over. Each participant experiences four rounds of driving differentiated by different weather conditions (clear weather, rain, snow, and fog). The impact of weather on takeover behaviour has been reported in previous research (Li et al., 2018).

As shown in Table 1, several dependent variables were adopted to quantify participants' takeover performance and attitude.

A hasty takeover is adopted as a measurement for takeover quality. It refers to any takeover where drivers execute the first active input to the level 3 automated vehicle before they have completely switched to the position of being ready for driving, which could make the takeover risky. The first active input to the vehicle has been previously defined as a manoeuvre of changing the steering wheel angle by at least 2 degrees and/or a movement of 10% of the accelerator or brake pedal positions (Gold et al., 2013b; Lu et al., 2016; Li et al., 2018; Li et al., 2019b; Li et al., 2019d). The position that is ready for driving refers to the position when drivers have moved their eyes to the driving direction (centre line of the steering wheel angle) and have put both their hands on the steering wheel and their feet on the pedals.

Driver's takeover behaviour refers to the type of reaction strategy that driver adopted in response to the car ahead, for example, steering only or steering and braking.

In addition, the time aspects of takeover include motor readiness time, takeover time and indicator time (Li et al., 2018; Li et al., 2019b; Li et al., 2019d; McDonald et al., 2019; Zhang et al., 2019a). Motor readiness time is the time between the HAV's initiation of the takeover request and the point when participants have completely switched to the position that is ready for driving. It measures how quickly the participants respond to the takeover request. Takeover time refers to the time between the takeover request and the point when drivers generate their first active input to the automated vehicle. It was used to quantify how quickly the participants input the control to the vehicle. Finally, indicator time is the time between the takeover request and the driver's input of the indicator signal for a lane change. It reflects the speed of a participant's decision to change lane to avoid the potential collision to the stationary car.

The time to collision (TTC) is an important parameter reflecting the level of the danger of a potential crash (van der Horst and Hogema, 1993; Stevens, 2000). TTC means 'the time required for two vehicles to collide if they continue at their present speed and on the same path' (Hayward, 1972; Happee et al., 2017). The minimal TTC that participants exhibited during the situation of reassuming the control of the level 3 automated vehicles has been commonly adopted to measure the quality and criticality of takeover behaviour (Körber et al., 2016; Happee et al., 2017; Gold et al., 2018). After the level 3 automation

Table 1
Overview of the dependent variables.

Dependent variables	*Data Type*	*Unit*	*Data collection method*
Motor readiness time	Continuous	Seconds	Observation
Takeover time	Continuous	Seconds	Driving simulator
Indicator time	Continuous	Seconds	Driving simulator
Time to collision (TTC)	Continuous	Seconds	Driving simulator
Resulting acceleration	Continuous	m/s^2	Driving simulator
Steering wheel angle	Continuous	Degrees	Driving simulator
Hasty takeover	Nominal	Count	Driving simulator
Collisions and critical encounters (CCE)	Nominal	Count	Driving simulator
Takeover behaviour	Nominal	Count	Driving simulator
Attitude	Ordinal	N/A	7-Likert Scale Questionnaire

system encounters a system limitation (stationary car blocking the road ahead in this study) and initiates a request to the participants in the vehicle to take over control, the TTC continues to decline until the participants brake or perform a lane change to prevent the automated vehicle from colliding to the system limitation (Happee et al., 2017; Gold et al., 2018). A TTC value of zero reflects a crash. The minimal TTC was derived up to the collision clearance point of the takeover situation (Happee et al., 2017; Gold et al., 2018). To determine the collision clearance point, this research adopted a widely-used lateral position-based definition which is the point where the centre of the automated vehicle departed the current lane where the system limitation (stationary car blocking the road ahead) happens (Gold et al., 2018).

In addition, the driver's resulting acceleration and steering wheel angle during the takeover process are adopted to measure takeover quality. The observation window is between the point when the driver receives the takeover request from the automation system to the collision clearance point where the centre of the automated vehicle departed the current lane of the system limitation.

Resulting acceleration reflects the force that the car has to pass to the road. The higher this value, the bigger the chance, and it could reach the maximum physical limit of the braking manoeuvres centred on the car tyre; and therefore in this case the driving is considered to be less stable and more dangerous (Gold et al., 2013a; Lu et al., 2016; Li et al., 2018; Li et al., 2019c; Li et al., 2019d).

It is calculated according to the maximum longitudinal and lateral acceleration, as the following Eq. (2) shows:

$$ResultingAcceleration = \sqrt{MaxLongitudinalAcc^2 + MaxLateralAcc^2} \quad (2)$$

Steering wheel angle refers to the standard deviation in degrees of the central line of the steering wheel. It is a widely used measurement to quantify takeover quality by reflecting the stability of the driver's takeover (Stevens, 2000; Stevens et al., 2002; Körber et al., 2016; Clark and Feng, 2017; Li et al., 2018; Li et al., 2019b; Li et al., 2019d; McDonald et al., 2019). A smaller value of the steering wheel angle represents a more stable takeover.

The numbers of collisions and critical encounters (CCEs) which occurred during the experiments were used to assess the quality of the takeover. The number of collisions involves all the crashes which happened during takeover, and the number of critical encounters includes any takeover with a minimum TTC of <1.5 s, which is deemed as the time threshold for which human drivers are highly likely to be involved in collisions (van der Horst and Hogema, 1993).

Finally, participant's overall attitude towards the level 3 automated vehicle was measured by the 7-Likert scale questionnaire (1-Strongly Disagree to 7-Strongly Agree) after all the driving sessions end.

2.5. Research procedure and data analysis

The procedure used in the study was, firstly to select the method and design the experiments. The investigation plans were then evaluated by the Newcastle University Ethical Committee. After approval for the study was received, the researcher conducted a risk assessment following advice from Newcastle University's Lone Working Safety Policy as well as guidance in *The Pathway to Driverless Cars: Code of Practice for Testing* (DfT, 2015) before starting to work in the driving simulator laboratory. The potential risks to participants and researchers when conducting this study were identified and corresponding risk management plans were formulated which were then reviewed by other members of the research team. Then, the recruitment of older and younger old people was conducted through the older people user group-VOICE as well as personal approaches in Newcastle upon Tyne. Before subjects arrived, the driving simulator as well as the level 3 automated driving scenario were set up and tested. When the subjects arrived at the lab, the subjects' driving licences were checked, and a safety briefing was delivered. Then, they were informed that their participation of the study was entirely voluntary and that they were free to withdraw at any time during the study without having to provide reasons, that all data collected would be anonymised and not identifiable and access to it limited to the research team; and any material containing image of their faces would be completely blurred. Then, they completed the research consent form and the participant information questionnaire. Next, they were guided to the driving simulator, and before starting the experiment, they were given considerable time to become familiar with the vehicle controls of the driving simulator using a manual driving scenario until they verbally indicated that they were comfortable and ready for the experiment. The level 3 automated driving scenario was then explained briefly. Participants were informed that the scenario started with automated driving where they should completely disengage from the driving by taking their hands off of the steering wheel, with their feet off the pedals, and to read out loud the material displayed on the tablet when the vehicle was performing automated driving. They were informed to stop the reading task and to take over control of the vehicle as soon as possible if they received any requests to do so by the automation system. After taking over control of the vehicle, they should continue to keep driving until clearly informed to stop, obeying the speed limit, indicating (using the indicator) when changing lanes and driving as they would normally in real life.

The driving simulator collects a range of data with a frequency of 20 Hz. The data is in binary form and was then converted into ASCII format. Data analysis was performed using IBM SPSS Statistics.

3. Results

3.1. Participants annual mileage.

As indicated in Table 2, the younger old group (Mdn = 10000–15000 miles) had significantly longer annual mileage compared to the older old group (Mdn = 3000–6000 miles) as assessed by a Chi-square test, X^2 (4) = 13.861, p = 0.008.

3.2. Takeover behaviour and overall takeover performance

This section reports the results of the takeover behaviour and overall performance of participants when overtaking the stationary vehicle after having taken over control from the automation system. The takeover performance of all participants was illustrated in Fig. 3 using a PCA plot. It shows that the overall takeover performance of the older old people appears to vary more greatly than the younger older people.

Participants' takeover behaviour is displayed in Table 3. The majority of older drivers in both the younger and older groups responded to the presence of the stationary car by only steering into the next lane. The percentage who responded by only steering into the next lane is slightly higher in the group of people aged 70 and over compared to those aged 60 to 69. Chi-square test yielded that there is no significant difference in takeover behaviour between the two groups, X^2 (1) = 0.368, p = 0.544.

3.3. Hasty takeover and CCE

This section reports the results for hasty takeovers and CCEs that participants exhibited when taking over control from the automation system.

For hasty takeovers, the dotted red lines in the left-hand side of Fig. 3 represent y = x. If a data point falls on the left-hand side of the y = x line (the highlighted red area), this suggests that a driver exhibited a higher reaction time than takeover time, indicating that the driver generated active input to the controls of the automated vehicles before they had completely switched to the manual driving position. As Table 3 and Fig. 3 show, the younger old group had a slightly higher percentage of hasty takeover compared to the older old group. However, the difference was not statistically significant as assessed by a Chi-square test, X^2 (1) = 1.755, p = 0.185.

A CCE is defined as any takeover with a TTC<1.5 s (Li et al., 2019d) and the results are illustrated in the right-hand side of Fig. 4. If a data points fall below the y = 1.5 s line, it suggests that a CCE was exhibited by a driver in a test drive. As shown in Table 4, the group of drivers aged 70 and over exhibited a significantly higher rate of CCE compared to those aged 60 to 69 as assessed by a Chi-square test, X^2 (1) = 4.692, p = 0.030.

3.4. Motor readiness time

Motor readiness time (reaction time) measures how quickly participants responded to the takeover request issued by the automation system by adjusting to the position of being ready for driving after performing the reading task. The distribution of data and a descriptive analysis of motor readiness times are shown in Fig. 5 and Table 6. To investigate whether there is a significant difference in motor readiness time between older people aged 70 and over and those aged 60 to 69, an independent samples *t*-test was conducted. The results shown in Table 5 indicate that older people aged 70 and older (mean = 2.984 s, SD = 0.766 s) exhibited significantly slower motor readiness times compared to those aged 60 to 69 (mean = 2.715 s, SD = 0.713 s), $t(154) = 2.190$, $p = 0.030$.

3.5. Takeover time

Takeover time measures how quickly participants generated their first active input to the vehicle controls following the takeover request issued by the automation system. The distribution of data and a descriptive analysis of takeover time are shown in Fig. 6 and Table 6. To investigate whether there is a significant difference in takeover times between older people aged 70 and over and those aged 60 to 69, an independent samples *t*-test was conducted. The results shown in Table 5 indicate that older people aged 70 and older (M = 4.851 s, SD = 2.006) exhibit significantly slower takeover times compared to those aged 60 to 69 (mean = 3.491 s, SD = 1.130 s), $t(152.599) = 5.409$, $p < 0.001$.

Table 2
Annual mileage driven by participants.

Annual mileage (miles)	0–3000	3000–6000	6000–10000	10000–15000	15000+	Total
Younger old	0	3	3	8	1	15
Older old	6	7	9	2	0	24
Total	6	10	12	10	1	39

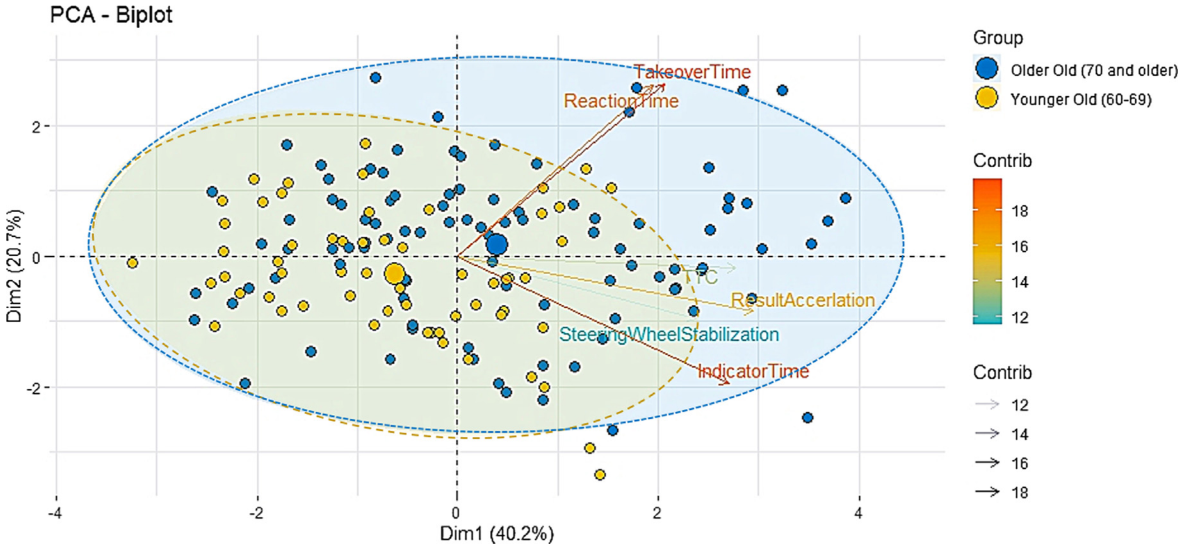

Fig. 3. Virtualization of overall takeover performance of the two age groups using a principal component analysis (PCA) biplot. The length of the arrows represents the variance of each dependent variable. The angles between arrows reflect the correlation among the six dependent variables. The closeness of the points represents approximately similar performance. Note: TTC in the biplot was presented as the lead time (20 s) minus the actual value of TTC.

Table 3
Steering and braking behaviours of the participants.

	Counts (and percentage) of takeover behaviour	
	Steer only	***Steer and brake***
Younger old group	45 (75%)	15 (25%)
Older old group	76 (79%)	20 (21%)

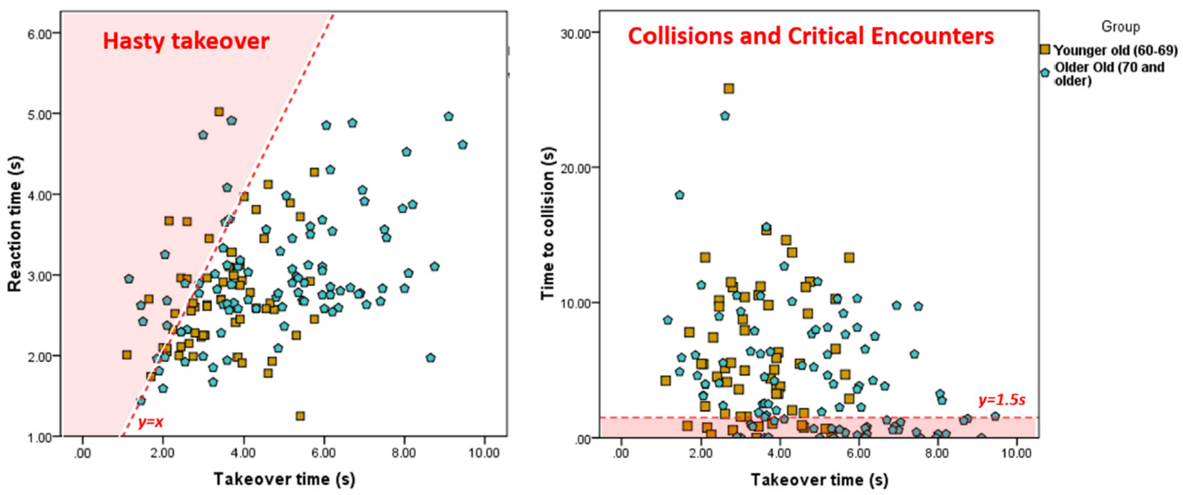

Fig. 4. Illustration of hasty takeovers and CCEs for the two age groups.

Table 4
Hasty takeovers and CCEs by the participants.

	Counts (and percentage) of CCEs and hasty takeovers	
	Hasty takeovers	***CCEs***
Younger old group	13 (22%)	11 (18%)
Older old group	13 (14%)	33 (34%)

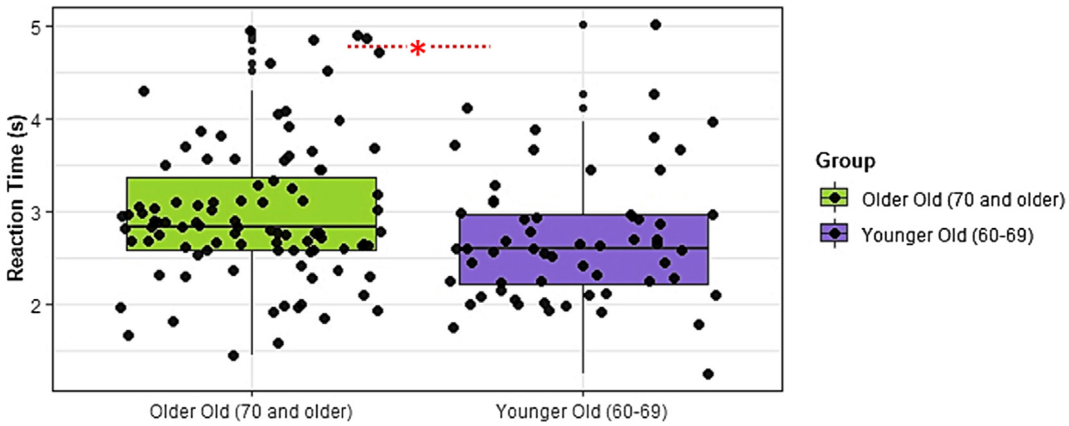

Fig. 5. Scatter and box plots showing the distribution of values of motor readiness time (reaction time) for the two age groups. The bottom and top of the boxes show the first (Q1) and third (Q3) quartiles, and the line within the box shows the median; the lower-limit shows the Q1-1.5* interquartile range (IQR), and the upper-limit the Q3 + 1.5 IQR. * denotes a significant difference between groups, where *= p ≤ 0.05.

Table 5
Independent samples T-test results for takeover performance by two age groups: motor readiness, takeover, and indicator time, TTC, resulting acceleration, and steering wheel stabilization.

	t	*df*	*p*	*Mean difference*	*95% confidence interval of the difference*	
					Lower	*Upper*
Motor readiness time (s)						
Age group (Older old 70 and over → Younger old 60–69)	2.190	154**	0.030	0.269↑	0.026	0.511
Takeover time (s)						
Age group (Older old 70 and over → Younger old 60–69)	5.409	152.599***	<0.001	1.360↑	0.863	1.857
Indicator time (s)						
Age group (Older old 70 and over → Younger old 60–69)	−0.690	154	0.491	−0.740↓	−2.859	1.378
Time to collision (s)						
Age group (Older old 70 and over → Younger old 60–69)	−2.234	154*	0.027	−1.707↓	−3.217	−0.198
Resulting Acceleration (m/s^2)						
Age group (Older old 70 and over → Younger old 60–69)	3.698	150.408***	<0.001	1.346↑	0.627	2.066
Steering wheel angle (degree)						
Age group (Older old 70 and over → Younger old 60–69)	4.773	146.063***	<0.001	4.732↑	2.773	6.692

Note: ↑=increase, ↓=decrease, significant differences were highlighted by *= p ≤ 0.05, **= p ≤ 0.01, ***= p ≤ 0.001.

3.6. Indicator time

Indicator time measures how quickly participants made the decision to deal with the incident by conducting a lane change following the takeover request issued by the automation system. The distribution of data and a descriptive analysis of indicator time are shown in Fig. 7 and Table 6. To investigate whether there is a significant difference in indicator time between older people aged 70 and over and those aged 60 to 69, an independent samples *t*-test was conducted. The results shown in Table 5 indicate that there was no significant difference between the indicator times of older people aged 70 and older (mean = 15.393 s, SD = 6.035 s) and those aged 60 to 69 (mean = 16.134 s, SD = 7.223 s), $t(154) = -0.690$, $p = 0.491$.

3.7. Time to collision (TTC)

TTC represents a valuable measure of takeover safety and measures the amount of time the driver has left until the collision with the stationary vehicle would occur. It is calculated up to the point where the centre of the automated vehicle departed the current lane that system limitation occurs. The distribution of data and a descriptive analysis of TTC are shown in Fig. 8 and Table 6. To investigate whether there is a significant difference in TTC between older people aged 70 and over and those aged 60 to 69, an independent samples *t*-test was conducted. The results shown in Table 5 indicate that older people aged 70 and older (mean = 4.473 s, SD = 4.409 s) exhibited significantly smaller TTCs compared to those aged 60 to 69 (mean = 6.181 s, SD = 4.996 s), $t(154) = -2.234$, $p = 0.027$.

Table 6
Descriptive analysis of results for the two age groups in reaction time, takeover time, indicator time, TTC, resulting acceleration, steering wheel angle and workload.

	Mean	*Median*	*SD*	*Min*	*Max*	*95% confidence interval*	
						Lower	*Upper*
Motor readiness time (s)							
Older old 70 and over	2.984	2.835	0.766	1.440	4.960	2.829	3.139
Younger old 60–69	2.715	2.605	0.713	1.250	5.02	2.531	2.899
Takeover time (s)							
Older old 70 and over	4.851	4.925	2.006	1.150	9.450	4.444	5.258
Younger old 60–69	3.491	3.450	1.130	1.100	5.750	3.199	3.782
Indicator time (s)							
Older old 70 and over	15.393	14.700	6.035	4.650	35.15	14.171	16.617
Younger old 60–69	16.134	16.250	7.223	3.900	36.10	14.268	18.000
Time to collision (s)							
Older old 70 and over	4.473	3.414	4.409	0.000	23.79	3.580	5.367
Younger old 60–69	6.181	5.100	4.996	0.000	25.810	4.890	6.181
Resulting Acceleration (m/s^2)							
Older old 70 and over	4.661	4.651	2.626	0.760	9.700	4.129	5.193
Younger old 60–69	3.314	2.718	1.909	0.840	7.990	2.821	3.808
Steering wheel angle (degree)							
Older old 70 and over	12.549	11.227	6.893	1.770	31.47	11.153	13.946
Younger old 60–69	7.817	5.632	5.411	2.390	29.16	6.419	9.215

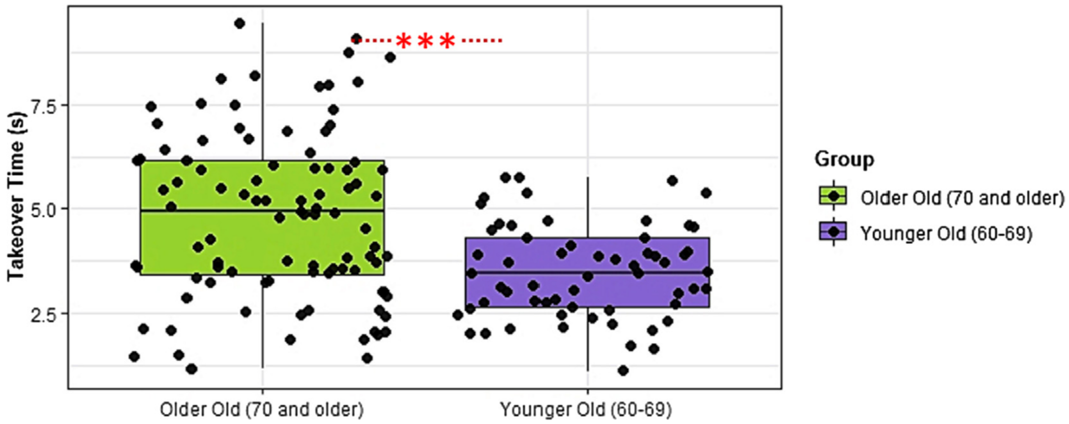

Fig. 6. Scatter and box plots showing the distribution of values of takeover time for two age groups. The bottom and top of the boxes show the first (Q1) and third (Q3) quartiles, and the line within the box shows the median; the lower-limit the Q1-1.5* interquartile range (IQR), and the upper-limit shows Q3 + 1.5 IQR. *** denotes a significant difference between the groups, where ***= $p \leq 0.001$.

3.8. Resulting acceleration

Resulting acceleration measures the maximum force that driver generated between the takeover request to the collision clearance point, where a greater value represents a more critical takeover. The distribution of data and a descriptive analysis of resulting acceleration is displayed in Fig. 9 and Table 6. To investigate whether the age group of older people has a significant impact on the value of resulting acceleration, an independent samples *t*-test was adopted. Results (Table 5) showed that older people aged 70 and older (mean = 4.661 m/s^2, SD = 2.626 m/s^2) exhibited significantly greater resulting acceleration compared to those aged 60 to 69 (mean = 3.314 m/s^2, SD = 1.909 m/s^2), $t(150.408) = 3.698$, $p < 0.001$.

3.9. Steering wheel stabilization

Steering wheel stabilization measures the standard deviation of the steering wheel angle that the driver exhibited when taking over control from the automated system. A greater value represents a less stable takeover. The distribution of data and a descriptive analysis of steering wheel stabilization are shown in Fig. 10 and Table 6. To investigate whether there is a significant difference in steering wheel stabilization between older people aged 70 and over and those aged 60 to 69, an

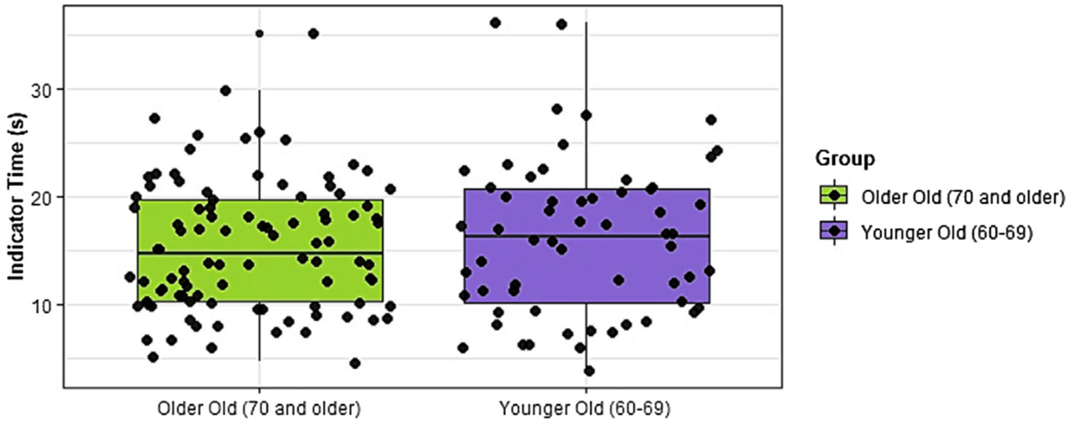

Fig. 7. Scatter and box plots showing the distribution of indicator time values for the two age groups. The bottom and top of the boxes show the first (Q1) and third (Q3) quartiles, and the line within the box shows the median; the lower-limit shows Q1-1.5* interquartile range (IQR), and the upper-limit the Q3 + 1.5 IQR.

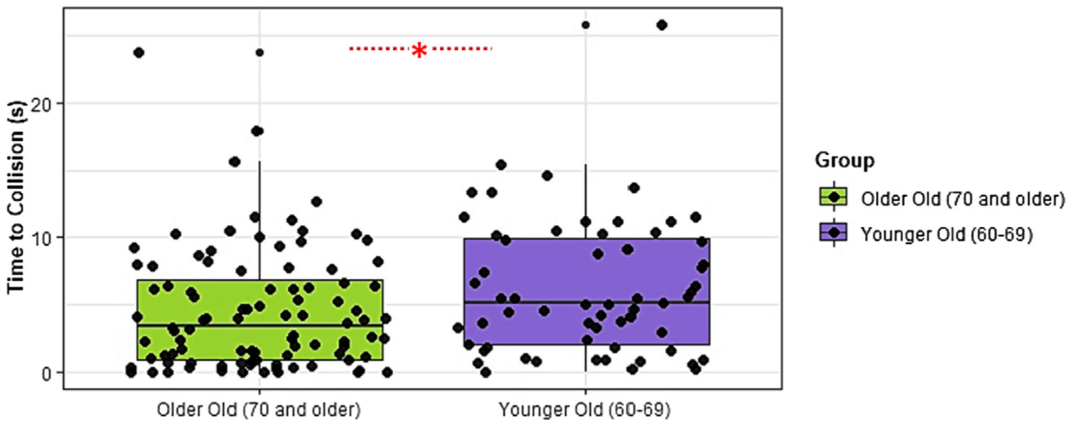

Fig. 8. Scatter and box plots showing the distribution of value of time to collision for two age groups. The bottom and top of the box show the first (Q1) and third (Q3) quartiles, and the line within the box shows the median; the lower-limit shows the Q1-1.5* interquartile range (IQR), and the upper-limit the Q3 + 1.5 IQR. * denotes a significant difference between the groups, where *= $p \leq 0.05$.

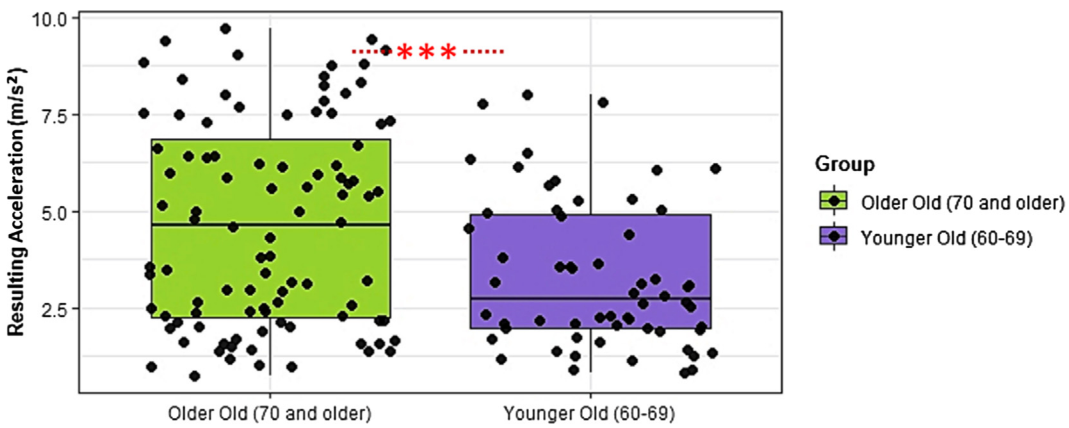

Fig. 9. Scatter and box plots showing the distribution of values of resulting acceleration for two age groups. The bottom and top of the boxes show the first (Q1) and third (Q3) quartiles, and the line within the box shows the median; the lower-limit the Q1-1.5* interquartile range (IQR), and the upper-limit shows Q3 + 1.5 IQR. *** denotes a significant difference between the groups, where ***= $p \leq 0.001$.

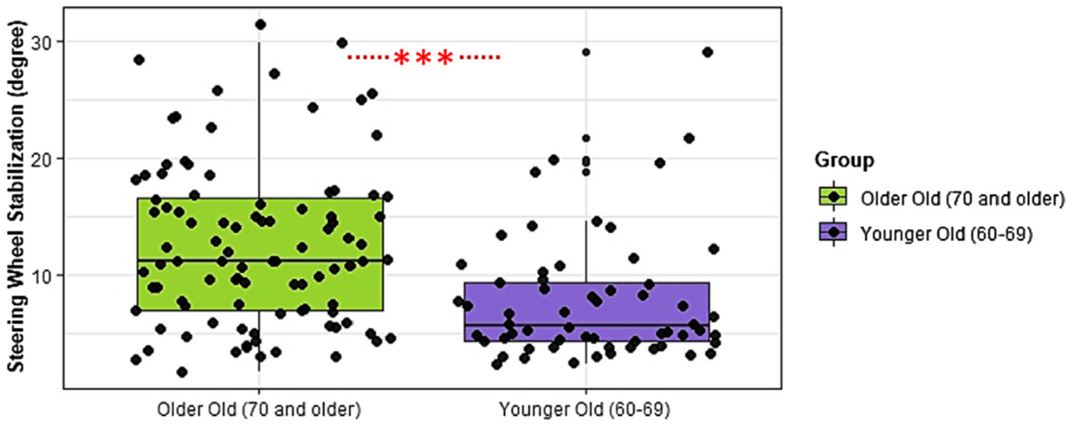

Fig. 10. Scatter and box plots showing the distribution of values of steering wheel stabilization for two age groups. The bottom and top of the boxes show the first (Q1) and third (Q3) quartiles, and the line within the box shows the median; the lower-limit the Q1-1.5* interquartile range (IQR), and the upper-limit shows Q3 + 1.5 IQR. *** denotes a significant difference between the groups, where ***= $p \le 0.001$.

Table 7
Summary of participants' attitudes towards the level 3 automated vehicle.

"The HAV is beneficial and helpful"	*Median*	*Mode*	*Mean*	*% Positive attitude*	*% Highly positive attitude*
Younger old group	5	5	5	73.3%	33.3%
Older old group	6	6	5.96	91.7%	79.2%
Overall	6	6	5.59	84.6%	61.5%

Note: A positive attitude refers to participants 'answering 5, 6 or 7. Highly positive attitudes refer to participants' answering 6 or 7.

independent samples *t*-test was conducted. The results shown in Table 5 indicate that older people aged 70 and older (mean = 12.549 degrees, SD = 6.893 degrees) exhibited significantly higher values of steering wheel stabilization compared to those aged 60 to 69 (mean = 7.817 degrees, SD = 5.411 degrees), $t(146.063) = 4.773$, $p < 0.001$.

3.10. Overall attitude

Older people's overall attitudes towards level 3 automated vehicles were examined using a 7-point Likert scale questionnaire. As Table 7 shows, 84.6% of old people expressed generally positive attitudes and 61.5% expressed highly positive attitudes.

The results of a Mann-Whitney *U* test showed that there was a statistically significant difference in old people's attitudes towards the level 3 automated vehicle between the younger old group and the older old group, U = 108.000, p = 0.031, with the older old people (Mdn = 6) exhibiting significantly more positive attitudes compared to the younger old people (Mdn = 5). The percentage showing positive attitude (7-Likert scale = 5,6 or 7) towards the automated vehicle was higher among older old group (91.7%) than the younger old group (73.3%). However, this different is not statistically significant as assessed by a Chi-square test, X^2 (1) = 2.383, p = 0.123. The percentage of older people showing highly positive attitude (7-Likert scale = 6 or 7) towards the automated vehicle was, however, significantly higher among older old group (79.2%) compared to the younger old group (33.3%), X^2 (1) = 8.193, p = 0.004.

4. Discussion

The current study aimed to investigate whether older people should be regarded as a homogeneous group in the context of interacting with automated vehicles. The performance and behaviour during the process of taking over control as well perceptions towards level 3 automated vehicles among older people from two sub-groups of old age-younger old group (60 to 69 years old) and older old group (70 years of age and over) was compared. The results show that the sub-group of old age has a significant effect on performance and behaviour when interacting with a level 3 automated vehicle.

Compared with younger older people in the age range of 60 to 69, the older old people aged 70 and over exhibited significantly longer times to disengage from the reading task and switch to the manual driving task by positioning their hands on the steering wheel, putting their feet on the pedals and directing their sight to the road (difference in motor readiness time: 0.27 s); moreover, they also executed significantly slower first active inputs to the vehicle controls by turning the steering wheel or pressing the pedals (difference in takeover time: 1.36 s). This corresponds with previous studies which found that reaction time slows as people age (Van Asselen and Ridderinkhof, 2000; Yang et al., 2015). In comparison with the current study which found that the mean takeover time is 3.49 s for the younger older people and 4.85 s of older old people when reassuming control from level 3 automated vehicle system, previous studies have yielded a much smaller mean takeover time among older people. For example, Körber et al. (2016) found older people exhibited a takeover time of 2.62 s when taking over control from the automated vehicle while being distracted by the 20 Questions task in zero traffic density conditions; and Wu et al. (2020) found a takeover time of 2.99 s among older people when they were assuming control of the automated vehicle while being engaged in non-driving related tasks (watching videos and playing games). This could be explained that the current study adopted a time budget of 20 s for older people to regain control of the automated vehicle whereas previous studies have adopted a much shorter time budget (6 s and 7 s) (Körber et al., 2016; Wu et al., 2020). Short warning time budget has been found to be linked with faster response (Mok et al., 2015). Another possible explanation could be that the less time older people have, the greater urgency they may have perceived during the reassuming control of automated vehicles, which may have reduced their reaction time to the takeover request (Edworthy et al., 2000).

Besides, this study adopted three time-related parameters to measure participants' takeover, the significant differences between the younger older people and older old people mainly lie in the two parameters of executing the takeover action (motor readiness time and takeover time). However, there is no significant difference between the two groups in terms of the time of making the decision to respond to the stationary car ahead (indicator time). This finding could be explained as that in the current study, participants on the level 3 automated vehicle were performing a mandatory reading task while suddenly being requested by the level 3 automation system to reassume control of the vehicle. In this situation, the old people on board must firstly perceive and understand the alert concerning retaking control initiated by the level 3 automation system, then switch their attention from the reading task to the task of executing the action of taking over driving control of the vehicle. Age is positively associated with the increased reaction time due to task-switching (Kray and Lindenberger, 2000; Van Asselen and Ridderinkhof, 2000), which could lead to the slower time to execute the takeover action among the older old people compared to their younger counterparts. In terms of the time of making decision to react to the system limitation, since the level 3 automated driving scenario in this study has adopted a relatively long time budget (20 s) for participants to react before reaching the system limitation. After obtaining the control of the vehicle there was still a relatively long distance between the automated vehicle and the stationary car ahead. The cautious nature of older people may facilitate them to accumulate more information about the driving environment to carefully and thoroughly think and plan the action for responding to the system limitation (Botwinick, 1966; Forstmann et al., 2011). This may have compensated for the age-related difference in their decision-making speed and resulted in a similar indicator time between the two groups.

In terms of the quality of takeover, the older subgroup manifested a significantly more abrupt and less stable operation of the steering wheel and pedals. This is in accordance that the age-related impaired limb mobility and flexibility as well as reduced muscle strength could affect drivers' ability to stably and accurately operate the steering wheel or shift their foot between the accelerator and brake pedals to execute an effective manoeuvre (Kallman et al., 1990; Marmeleira et al., 2009). In addition, older old people's performance of responding to the system limitation was significantly worse (significantly smaller TTC) compared to the younger subgroup, although the time they spent to make the decision of responding to the system limitation (indicator time) was not significantly different. This may suggest that although a long time budget may have minimised the age-related difference in decision-making speed between the older old people and younger old people, it did not fully compensate for the negative impact of age on the reaction performance among the two groups. This finding is in accordance with a study by Vaportzis et al. (2013), although their research is not fully comparable with the current study, they observed similar findings that when performing complicated reaction time tasks, older people reacted as fast as their younger counterparts, but their performance is significantly worse. Future research is needed to investigate the age-related changes in the relationship between decision-making time and task performance among older people of different age sub-groups when interacting with automated vehicles.

In general the findings of this study support those of previous research into the impact of age on driving performance in conventional cars, indicating that older old people (aged 70 and over) are more risky than those aged 60 to 69 in terms of road safety and likely involvement in car crashes, and their fatality rate increases sharply due to age-related physical fragility (Rakotonirainy et al., 2012; Christopher, 2013). The findings of the current study can be explained in terms of the fact that the key innovation of level 3 automation is to allow the drivers on-board to be both physically and mentally disengaged from the vehicle driving process so that they can safely engage in non-driving related tasks (SAE, 2014; Li et al., 2018; Li et al., 2019b; Li et al., 2019d). When the automation system unexpectedly initiates the request of intervene, the drivers on-board must stop performing the non-driving related activities, perceive the environment, regain their situation awareness, process the perceptual information received, make decisions and execute decisional processes necessary to take back control of the vehicle and operate it safely to prevent a collision with the stationary car ahead in the driving lane (Endsley, 1995; Li et al., 2018; Li et al., 2019d). This means that the entire process of the transition of control would demand a driver's level 2 situation awareness so as to perceive all of the relevant information in the environment in which control is to be taken over, as well as level 3 situation awareness in order to fully comprehend all of the information perceived in the situation in order to gain control of the vehicle at the operational and tactical levels (Michon, 1985; Endsley, 1995; Matthews et al., 2001; Li et al., 2019d). Such a complicated process would require the combination of a variety of visual, auditory, cognitive and psychomotor functionalities on the part of the driver, including sensory perception, auditory acuity, selective and divided attention, and executive cognitive functions, as well as physical strength and functional fitness (Rodríguez-Aranda et al., 2006; Shanmugaratnam et al., 2010; Emmerson et al., 2013; Milanović et al., 2013; Murman, 2015). Age-related impairments on these functionalities are generally more significant among older old people aged 70 and over compared to those aged

60 to 69 (Deaton and Parasuraman, 1993; Isler et al., 1997; Bigler, 2012; Milanović et al., 2013; Murman, 2015; Karthaus and Falkenstein, 2016).

Moreover, results showed that greater variation has been found in most of the measurements quantifying takeover performance (e.g., reaction time, takeover time, resulting acceleration and steering wheel angle) among older old group compared to the younger older group. This could be explained as that there is a positive relationship between the age of age group and the level of variation in their cognitive, physical as well as sensory functionalities (Lafortune et al., 2009; Santoni et al., 2015). This finding creates a need for the future research to group older people based on the variation of their functional impairments as well as capabilities and explore how such age-related variation impact their performance when interacting with automated vehicles. The outcome of such research could be useful to distinguish the varied needs among older people and provide tailored support and assistance correspondingly when using automated vehicles. Moreover, post-hoc finding of the participants' annual mileage of the current study showed that the younger old group (Mdn = 1000 0–15000 miles) exhibited significantly longer annual mileage compared to the older counterpart (Mdn = 3000–6000 miles), which corresponds to previous evidence that the annual mileage travelled by those aged 70 and over is about half of that for younger older people aged 60 to 69 (DfT, 2014). The lower annual mileage has been found to be positively associated with the higher prevalence of kidney disease, cognitive decline and far vision impairments among older people (Lyman et al., 2001). Such greater levels of decline in sensory, cognitive, and psychomotor functionalities among older old people could potentially make them more disadvantaged and vulnerable in terms of fulfilling the complicated and demanding tasks of reassuming control from level 3 automated vehicles.

Overall, the findings of the current study correspond with those of previous research which emphasize that older people should not be treated as a homogeneous group in terms of transport and mobility. Difference in needs, requirements and driving behaviour between younger older people and older old people should be clearly recognised and fully understood in order to better support their wellbeing and quality of life in an ageing society (Alsnih and Hensher, 2003).

Regarding older people's perceptions towards automated vehicles, the current research finds that the majority of older people who participated in this study (84.6%) exhibited optimistic and confident attitudes (responses on the 7-Likert scale of 5,6 and 7) towards level 3 automated vehicles. Moreover, 61.5% expressed highly positive attitude (responses of 6 and 7). This supports the argument that older people are keen to accept new technology (Vaportzis et al., 2017). In addition, it corresponds with a previous study by the present authors exploring older people's perception and requirements of automated vehicle from a qualitative perspective where older people were positive about the level 3 automated vehicles and perceived a variety of beneficial use (Li et al., 2019c). One explanation for the current findings could involve the first-hand experience of participants interacting with the automated vehicle on the driving simulator (Li et al., 2019c). Old people are not always prepared to be digitally engaged (Damodaran and Olphert, 2015) and they represent a major proportion of the group who has limited access to the internet (ONS, 2014). It is possible that, before participating in the current research, they may not have had sufficient and detailed information about human–machine interaction in level 3 automated vehicles and may have had little understanding of what they could signify in terms of their independence and mobility. Therefore, the hands-on experience gained in this study may have been an important facilitator of their positive perceptions (Lee et al., 2015; Li et al., 2019c). Meanwhile, although the older old participants in this study exhibited a significantly poorer performance in taking over control from the automated vehicle, they expressed significantly more positive attitudes towards level 3 automated vehicles compared to their younger old counterparts. One possible reason for this could be that 70 years of age is the point at which driving licences expire in the UK. In order to renew their driving licences, drivers must declare to that DVLA that they are fit to drive and do not have any medical conditions affecting their safe driving abilities (Christopher, 2013; DVLA, 2019). Because of this, the opportunity to interact with a level 3 automated vehicle in this study might have had a greater impact on participants aged 70 and over and they may have appreciated the greater potential of vehicle automaton in terms of compensating for their functional impairments. They could have realised that it might represent a potential alternative future mobility option rather than having to inform the DVLA and stop driving altogether, which may also have resulted in significantly higher positive attitudes towards automated vehicles (Li et al., 2019c; Musselwhite and Scott, 2019).

5. Conclusion

Exploring the future mobility options for older people is imperative for maintaining wellbeing and quality of life in an ageing society (Guo et al., 2010; Shergold et al., 2015; Li et al., 2019d). Although the potential advantages of vehicle automation for older people's mobility, independence and wellbeing have already been recognised in previous research, older people have been regarded as a homogeneous group. A key knowledge gap remains concerning whether older people should be treated as a homogeneous group in terms of their capabilities, performance, and perceptions when interacting with automated vehicles. To answer this question, the current driving simulator study aimed to investigate the impact of age on the performance and perception of interacting with a level 3 automated vehicle by distinguishing between two subgroups of older people who are-younger older people (aged 60–69 years) or older old people (aged 70 and over years). The findings of the investigation indicate that older people should not be regarded as a single cohort when researching age and vehicle automation. Those in different subgroups of old age exhibit significantly different performance and perceptions when interacting with the level 3 automated vehicles. Compared to the younger old subgroup (aged 60–69), older old subgroup (aged 70 and over) showed more disadvantaged performance when taking back control over the level 3 automated vehicle.

Specifically, they took a longer time to react to the takeover request and to be ready for manual driving, they took over the control of the vehicle more slowly, and their takeover quality was less stable and more critical. In addition, greater variation in most measurement for takeover performance was found among the older old people. However, although both the younger and older subgroups of older people exhibited positive perceptions towards level 3 automation, the older old people's perceptions were significantly more positive. This study demonstrates the importance of regarding older people as a heterogeneous group in terms of the impact of age on older people's performance, capability, needs and requirements when interacting with automated vehicles.

The findings of this study have important implications for the development and realisation of age-friendly automated mobility. For policymakers, the findings indicate that, in terms of relevant policy regarding eligibility for operating level 3 automated vehicles, the current age threshold of 70 years as adopted by DVLA (2019) for the renewal of driving licences for conventional human-operated vehicles where drivers must declare their fitness to drive may still be worthy of consideration if vehicles equipping with level 3 automation systems are to be released on the market. To ensure the safety of people on-board and that of other road users, fitness to take over control and any potential functional impairments affecting taking over control could be important criterions when reviewing eligibility to operate level 3 automated vehicles as well as developing regulations regarding the support required for specific user groups. Additional research and tests need to be devised and undertaken to confirm this. Moreover, there may also be a need to promote the development of automated vehicles with higher autonomous functionalities (SAE levels 4 or 5) as a future mobility option for older people, (Li et al., 2018), which would be especially useful for the older old who adopt regulatory driving practices as well as those who have ceased driving. The present findings also reinforced the importance of not regarding older people as a homogeneous group and of distinguishing between the different functional declines, capabilities, needs and requirements among different subgroups of older people when researching mobility and ageing issues (Alsnih and Hensher, 2003; Gallucci et al., 2009; Christopher, 2013). In addition, the current research highlights the importance of those in the medical professionals and the ageing and vehicle automation research communities working collaboratively to more precisely understand older people's sensory, cognitive and psychomotor needs when interacting with automated vehicles and to explore suitable and age-friendly future mobility alternatives for them. For car makers and original equipment manufacturers (OEMs), the current findings highlights the importance of enabling end-users to experience automated vehicles to enrich their perceptions, and strengthen the significance of incorporating older people's needs and performance capacities in the development process (Li et al., 2019c). With the UK's Government recognising that the Future of Mobility and the Ageing Society being two of the four Grand Challenges that the Industrial Strategy are underpinned by – illustrates that the research is addressing important current issues and opportunities in the UK to make automated vehicle useable by the whole population and in particular the growing number of older people who aspire to remain mobile for longer (HMG, 2017).

Although this study yielded important knowledge, there are still limitations. To begin with, the current study adopted a quantitative methodology to compare the performance and perceptions of two subgroups of older people aged 60 to 69 and 70 and above. Future research is necessary to explore the differences in acceptance, needs and requirements in relation to vehicle automation among younger old and older old groups from a qualitative perspective. Also, the current research enabled older people to resume the control of the vehicle from the level 3 automated driving system under four types of weather conditions (clear weather, rain, snow and fog). However, the level 3 automated driving scenario implemented on the particular driving simulator has only included the visual impact of adverse weather conditions including visual distractions and reduced visibility (Li et al., 2018). Some other negative affect of adverse weather such as the effect on road surface, including slippery surfaces, longer braking distances, cumulative snow, were not considered. In addition, the speed of vehicle under different weather conditions were assumed same. New plan has been introduced to design and develop an enhanced level 3 automated driving scenario fully incorporating the impact of adverse weather not only on visual distractions and reduced visibility but also on the road surface and vehicle speed. In addition, more types of adverse weather conditions will be added to the enhanced level 3 automated driving scenarios, such as night snow, night rain, night fog, windy snow, in addition to the existing four. Then, a new piece of research specifically focusing on how adverse weather conditions would affect different subgroups of older people will be conducted using the enhanced scenario. Moreover, due to the limitation of the existing level 3 automated driving scenario, the current study only adopted a lateral position-based definition of TTC to evaluate the criticality of the takeover situation (Happee et al., 2017; Gold et al., 2018). However, such definition does not consider the vehicle heading which decides if the straight-line trajectory of the current vehicle path will result in a crash with the stationary car ahead (Happee et al., 2017). It is necessary for the future research to also consider the vehicle heading-based definition of TTC which is calculated based on the collision clearance point where the straight-line trajectory of vehicle path does not overlay with the stationary car ahead anymore (Happee et al., 2017). Apart from that, the current research suggest that the older subgroup of old people exhibit disadvantaged performance during the transition of control from the automated vehicle, and so worthwhile future research could identify factors contributing to this finding as well as explore and evaluate suitable support and assistance tailored for them. This study adopted sub-group of old age as the between-subject independent variable, there are other between-subjects factors present, for example, gender, older people's self-regulatory driving behaviour, older people's self-reported functional impairments, older people's experience of using Advanced driver-assistance systems (ADAS). It is imperative for the future research to explore how these factors could influence older people's interaction with automated vehicles. Also, this research observed substantial variation in performance among older people aged 70 and over, it would be important for future research to identify the factors contributing to the great variation and explore mitigation strategies for older people performed poorly when using automated vehicles.

The sample of participants in the current study was not equal for the younger and older sub-groups of older people and it under-represented the oldest old people aged 85 and over, and it could be important for future research to adopt equal sample size for the two groups and also explore if those aged 85 and over might interact with automated vehicles in different ways compared to younger older counterparts as well as middle-aged people (Chen et al., 2019). Moreover, the current study adopted a single non-driving related reading task to disengage participants from driving. Considering that multitasking significantly worsen the takeover performance (Li et al., 2019a), future research could investigate what this means for the older people in terms of interacting with automated vehicles. The automated driving duration adopted in this study is one minute, future research could explore older people's interaction and behaviour when they expose to automated driving for a much longer duration. Finally, future interdisciplinary research collaboration involving medical, ageing and vehicle automation research professionals could be useful not only to explore age-friendly mobility solutions for the older people but also to facilitate the delivery of user-friendly future mobility for people of all ages and ultimately to benefit the entire society.

CRediT authorship contribution statement

Shuo Li: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing - original draft, Writing - review & editing, Visualization, Resources, Project administration. **Phil Blythe:** Conceptualization, Methodology, Writing - original draft, Writing - review & editing, Visualization, Resources, Funding acquisition, Supervision, Project administration. **Yanghanzi Zhang:** Formal analysis, Visualization, Data curation, Writing - original draft, Writing - review & editing. **Simon Edwards:** Project administration, Supervision, Writing - review & editing. **Jin Xing:** Writing - review & editing. **Weihong Guo:** Conceptualization, Methodology, Supervision, Project administration, Writing - review & editing, Funding acquisition. **Yanjie Ji:** Writing - review & editing. **Paul Goodman:** Writing - review & editing. **Anil Namdeo:** Conceptualization, Methodology, Supervision, Writing - review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We appreciate the time and effort of all the participants of this study. This research is part of a PhD research project at Newcastle University and we acknowledge the on-going support of the UK's Engineering and Physical Sciences Research Council (EPSRC) through the following funding wards: LC Transform (EP/N010612/1); Helping Older Drivers continue driving safer for longer (EP/K037579/1); the Centre for Energy Systems Integration (EP/P001173/1). The authors also acknowledge the advice and support of the National Innovation Centre for Ageing (NICA) and the UK Department for Transport (DfT).

References

Alsnih, R., & Hensher, D. A. (2003). The mobility and accessibility expectations of seniors in an aging population. *Transportation Research Part A: Policy and Practice, 37*(10), 903–916.
Attebo, K., Mitchell, P., & Smith, W. (1996). Visual acuity and the causes of visual loss in Australia: The blue mountains eye study. *Ophthalmology, 103*(3), 357–364.
Ball, K., Owsley, C., Stalvey, B., Roenker, D. L., Sloane, M. E., & Graves, M. (1998). Driving avoidance and functional impairment in older drivers. *Accident Analysis & Prevention, 30*(3), 313–322.
Bellet, T., Paris, J. C., & Marin-Lamellet, C. (2018). Difficulties experienced by older drivers during their regular driving and their expectations towards advanced driving aid systems and vehicle automation. *Transportation Research Part F: Traffic Psychology and Behaviour, 52*, 138–163.
Berk, L. E. (2018). *Development through the lifespan* (seventh ed.). Hoboken, NJ: Pearson Education Inc.
Bigler, E. D. (2012). Symptom validity testing, effort, and neuropsychological assessment. *Journal of the International Neuropsychological Society, 18*(4), 632–640.
Botwinick, J. (1966). Cautiousness in advanced age. *Journal of Gerontology, 21*(3), 347–353.
Charlton, J. L., Oxley, J., Fildes, B., Oxley, P., Newstead, S., Koppel, S., & O'Hare, M. (2006). Characteristics of older drivers who adopt self-regulatory driving behaviours. *Transportation Research Part F: Traffic Psychology and Behaviour, 9*(5), 363–373.
Chen, T., Sze, N. N., & Bai, L. (2019). Safety of professional drivers in an ageing society–A driving simulator study. *Transportation Research part F: Traffic Psychology and Behaviour, 67*, 101–112.
Christopher, G. B. (2013). The licensing and safety of older drivers in Britain. *Accident Analysis & Prevention, 50*, 732–741.
Clark, H., & Feng, J. (2017). Age differences in the takeover of vehicle control and engagement in non-driving-related activities in simulated driving with conditional automation. *Accident Analysis & Prevention, 106*, 468–479.
Damodaran, L. and Olphert, W. (2015) How are attitudes and behaviours to the ageing process changing in light of new media and new technology?: How might these continue to evolve by 2025 and 2040? Government office for science. [Online]. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/455176/gs-15-17-future-ageing-attitudes-new-technology-er08.pdf.
Deaton, J. E., & Parasuraman, R. (1993). Sensory and cognitive vigilance: Effects of age on performance and subjective workload. *Human Performance, 6*, 71–97.
DfT (2014) National Travel Survey: England 2014: How people travel-car. Department for Transport. [Online]. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/458414/how-people-travel-car.pdf.
DfT (2015). *The pathway to driverless car: A code of practice for testing*. Department for Transport.
DfT (2017) National Travel Survey: England 2016. [Online]. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/633077/national-travel-survey-2016.pdf.
Dulisse, B. (1997). Older drivers and risk to other road users. *Accident Analysis & Prevention, 29*(5), 573–582.

DVLA (2019) Assessing fitness to drive a guide for medical professionals. Driver & Vehicle Licensing Agency. [Online]. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/866655/assessing-fitness-to-drive-a-guide-for-medical-professionals.pdf.
Eberhard, J. (2008). Older drivers'"high per-mile crash involvement": The implications for licensing authorities. *Traffic Injury Prevention, 9*(4), 284–290.
Eby, D.W. and Molnar, L.J. (2012) Has the time come for an older driver vehicle? The University of Michigan Transportation Research Institute. [Online]. Available at: https://deepblue.lib.umich.edu/handle/2027.42/89960.
Edworthy, J., Hellier, E., Walters, K., Weedon, B., & Adams, A. (2000). *Human Factors and Ergonomics Society Annual Meeting CA*. Los Angeles. Sage.
Emmerson, C., Guo, W., Blythe, P., Namdeo, A., & Edwards, S. (2013). Fork in the road: In-vehicle navigation systems and older drivers. *Transportation Research Part F: Traffic Psychology and Behaviour, 21*, 173–180.
Endsley, M. R. (1995). Toward a theory of situation awareness in dynamic systems. *Human Factors, 37*(1), 32–64.
Ferreira, I. S., Simões, M. R., & Marôco, J. (2013). Cognitive and psychomotor tests as predictors of on-road driving ability in older primary care patients. *Transportation Research part F: Traffic Psychology and Behaviour, 21*, 146–158.
Flemisch, F., Kelsch, J., Löper, C., Schieben, A. and Schindler, J. (2008) 'Automation spectrum, inner/outer compatibility and other potentially useful human factors concepts for assistance and automation', in Waard, D.d., Flemisch, F., Lorenz, B., H. Oberheid and Brookhuis, K. (eds.) Human Factors for Assistance and Automation. Maastricht: Shaker, pp. 1 – 16.
Forman, D. E., Berman, A. D., McCabe, C. H., Baim, D. S., & Wei, J. Y. (1992). PTCA in the elderly: The "young-old" versus the "old-old". *Journal of the American Geriatrics Society, 40*(1), 19–22.
Forstmann, B. U., Tittgemeyer, M., Wagenmakers, E. J., Derrfuss, J., Imperati, D., & Brown, S. (2011). The speed-accuracy tradeoff in the elderly brain: A structural model-based approach. *Journal of Neuroscience, 31*(47), 17242–17249.
Gallucci, M., Antuono, P., Ongaro, F., Forloni, P. L., Albani, D., Amici, G. P., & Regini, C. (2009). Physical activity, socialization and reading in the elderly over the age of seventy: What is the relation with cognitive decline? Evidence from "The Treviso Longeva (TRELONG) study. *Archives of Gerontology and Geriatrics, 48*(3), 284–286.
Gold, C., Damböck, D., Lorenz, L., & Bengler, K. (2013). *Proceedings of the human factors and ergonomics society annual meeting*. Los Angeles: SAGE.
Gold, C., Happee, R., & Bengler, K. (2018). Modeling take-over performance in level 3 conditionally automated vehicles. *Accident Analysis & Prevention, 116*, 3–13.
Gold, C., Körber, M., Lechner, D., & Bengler, K. (2016). Taking over control from highly automated vehicles in complex traffic situations: The role of traffic density. *Human Factors, 58*(4), 642–652.
Gold, C., Lorenz, L., Damböck, D., & Bengler, K. (2013). *'Partially automated driving as a fallback level of high automation', 6*. Munich, Germany: Tagung Fahrerassistenzsysteme.
Guo, A. W., Brake, J. F., Edwards, S. J., Blythe, P. T., & Fairchild, R. G. (2010). The application of in-vehicle systems for elderly drivers. *European Transport Research Review, 2*(3), 165–174.
Guo, W., Blythe, P. T., Edwards, S., Pavkova, K., & Brennan, D. (2013). Effect of intelligent speed adaptation technology on older drivers' driving performance. *IET Intelligent Transport Systems, 9*(3), 343–350.
Happee, R., Gold, C., Radlmayr, J., Hergeth, S., & Bengler, K. (2017). Take-over performance in evasive manoeuvres. *Accident Analysis & Prevention, 106*, 211–222.
Hayward, J. C. (1972). Near miss determination through use of a scale of danger. *Highway Research Record, 384*(1972), 24–34.
HMG (2017) Industrial strategy: Building a Britain fit for the future. [Online]. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/664563/industrial-strategy-white-paper-web-ready-version.pdf.
Howcroft, J., Knoefel, F., Wallace, B., Goubran, R., Porter, M. M., & Marshall, S. (2019). Impact of health differences and longitudinal changes on deceleration driving patterns in older adult drivers. *Transportation Research part F: Traffic Psychology and Behaviour, 60*, 137–146.
Huang, G., & Pitts, B. (2020). *International conference on human-computer interaction Copenhagen, Denmark*. Cham: Springer.
Isler, R. B., Parsonson, B. S., & Hansson, G. J. (1997). Age related effects of restricted head movements on the useful field of view of drivers. *Accident Analysis & Prevention, 29*(6), 793–801.
Jette, A. M., & Branch, L. G. (1992). A ten-year follow-up of driving patterns among the community-dwelling elderly. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 34*(1), 25–31.
Kallman, D. A., Plato, C. C., & Tobin, J. D. (1990). The role of muscle loss in the age-related decline of grip strength: Cross-sectional and longitudinal perspectives. *Journal of Gerontology, 45*(3), M82–M88.
Karthaus, M., & Falkenstein, M. (2016). Functional changes and driving performance in older drivers: Assessment and interventions. *Geriatrics, 1*(2), 12.
Körber, M., Gold, C., Lechner, D., & Bengler, K. (2016). The influence of age on the take-over of vehicle control in highly automated driving. *Transportation Research Part F: Traffic Psychology and Behaviour, 39*, 19–32.
Kostyniuk, L. P., & Molnar, L. J. (2008). Self-regulatory driving practices among older adults: Health, age and sex effects. *Accident Analysis & Prevention, 40*(4), 1576–1580.
Kray, J., & Lindenberger, U. (2000). Adult age differences in task switching. *Psychology and Aging, 15*(1), 126.
Lafortune, L., Béland, F., Bergman, H., & Ankri, J. (2009). Health state profiles and service utilization in community-living elderly. *Medical Care, 47*(3), 286–294.
Ledger, S., Bennett, J. M., Chekaluk, E., & Batchelor, J. (2019). Cognitive function and driving: Important for young and old alike. *Transportation Research Part F: Traffic Psychology and Behaviour, 60*, 262–273.
Lee, C., Mehler, B., Reimer, B., & Coughlin, J. F. (2015). User perceptions toward in-vehicle technologies: Relationships to age, health, preconceptions, and hands-on experience. *International Journal of Human-Computer Interaction, 31*(10), 667–681.
Lee, H. C., Cameron, D., & Lee, A. H. (2003). Assessing the driving performance of older adult drivers: On-road versus simulated driving. *Accident Analysis & Prevention, 35*(5), 797–803.
Li, G., Braver, E. R., & Chen, L. H. (2003). Fragility versus excessive crash involvement as determinants of high death rates per vehicle-mile of travel among older drivers. *Accident Analysis & Prevention, 35*(2), 227–235.
Li, S., Blythe, P., Edwards, S., Goodman, P. and Hill, G. (2019a) The 26th intelligent transport systems world congress. Singapore.
Li, S., Blythe, P., Guo, W., & Namdeo, A. (2018). Investigation of older driver's takeover performance in highly automated vehicles in adverse weather conditions. *IET Intelligent Transport Systems, 12*(9), 1157–1165.
Li, S., Blythe, P., Guo, W., & Namdeo, A. (2019a). Investigating the effects of age and disengagement in driving on driver's takeover control performance in highly automated vehicles. *Transportation Planning and Technology, 42*(5), 470–497.
Li, S., Blythe, P., Guo, W., & Namdeo, A. (2019b). Investigation of older drivers' requirements of the human-machine interaction in highly automated vehicles. *Transportation Research Part F: Traffic Psychology and Behaviour, 62*, 546–563.
Li, S., Blythe, P., Guo, W., Namdeo, A., Edwards, S., Goodman, P., & Hill, G. (2019c). Evaluation of the effects of age-friendly human-machine interfaces on the driver's takeover performance in highly automated vehicles. *Transportation Research Part F: Traffic Psychology and Behaviour, 67*, 78–100.
Louw, T., Kuo, J., Romano, R., Radhakrishnan, V., Lenné, M. G., & Merat, N. (2019). Engaging in NDRTs affects drivers' responses and glance patterns after silent automation failures. *Transportation Research part F: Traffic Psychology and Behaviour, 62*, 870–882.
Lu, Z., Happee, R., Cabrall, C. D., Kyriakidis, M., & de Winter, J. C. (2016). Human factors of transitions in automated driving: A general framework and literature survey. *Transportation Research Part F: Traffic Psychology and Behaviour, 43*, 183–198.
Lyman, J. M., McGwin, G., & Sims, R. V. (2001). Factors related to driving difficulty and habits in older drivers. *Accident Analysis & Prevention, 33*(3), 413–421.
Marmeleira, J. F., Godinho, M. B., & Fernandes, O. M. (2009). The effects of an exercise program on several abilities associated with driving performance in older adults. *Accident Analysis & Prevention, 41*(1), 90–97.

Matthews, M., Bryant, D., Webb, R., & Harbluk, J. (2001). Model for situation awareness and driving: Application to analysis and research for intelligent transportation systems. *Transportation Research Record: Journal of the Transportation Research Board, 1779*, 26–32.

McDonald, A. D., Alambeigi, H., Engström, J., Markkula, G., Vogelpohl, T., Dunne, J., & Yuma, N. (2019). Toward computational simulations of behavior during automated driving takeovers: A review of the empirical and modeling literatures. *Human Factors*, 1–47.

McGwin, G., Jr, & Brown, D. B. (1999). Characteristics of traffic crashes among young, middle-aged, and older drivers. *Accident Analysis & Prevention, 31*(3), 181–198.

Melcher, V., Rauh, S., Diederichs, F., Widlroither, H., & Bauer, W. (2015). Take-over requests for automated driving. *Procedia Manufacturing, 3*, 2867–2873.

Michon, J. A. (1985). A critical view of driver behavior models: What do we know, what should we do? In L. Evans & R. Schwing (Eds.), *Human behavior and traffic safety* (pp. 485–520). New York: Plenum Press.

Milakis, D., & van Wee, B. (2020). *'Implications of vehicle automation for accessibility and social inclusion of people on low income, people with physical and sensory disabilities, and older people', in Demand for Emerging Transportation Systems*. Elsevier.

Milanović, Z., Pantelić, S., Trajković, N., Sporiš, G., Kostić, R., & James, N. (2013). Age-related decrease in physical activity and functional fitness among elderly men and women. *Clinical Interventions in Aging, 8*, 549.

Miller, D., Johns, M., Ive, H.P., Gowda, N., Sirkin, D., Sibi, S., Mok, B., Aich, S. and Ju, W. (2016) Exploring transitional automation with new and old drivers (No. 2016-01-1442). SAE Technical Paper.

Mok, B., Johns, M., Lee, K. J., Miller, D., Sirkin, D., Ive, P., & Ju, W. (2015). *'Emergency, automation off: Unstructured transition timing for distracted drivers of automated vehicles', 2015 IEEE 18th International Conference on Intelligent Transportation Systems*. Canary Islands, Spain: IEEE.

Morrison, D. A., Bies, R. D., & Sacks, J. (1997). Coronary angioplasty for elderly patients with "high risk" unstable angina: Short-term outcomes and long-term survival. *Journal of the American College of Cardiology, 29*(2), 339–344.

Murman, D. L. (2015). The impact of age on cognition. *Seminars in Hearing, 36*(3), 111–121.

Musselwhite, C. (2011). The importance of driving for older people and how the pain of driving cessation can be reduced. *Journal of Dementia and Mental Health, 15*(3), 22–26.

Musselwhite, C., & Scott, T. (2019). Developing a model of mobility capital for an ageing population. *International Journal of Environmental Research and Public Health, 16*(18), 3327.

O'Hern, S., Oxley, J., & Logan, D. (2015). Older adults at increased risk as pedestrians in Victoria, Australia: An examination of crash characteristics and injury outcomes. *Traffic Injury Prevention, 16*(sup2), S161–S167.

ONS (2014) Internet access quarterly update, Q1 2014. Office for National Statistics. [Online]. Available at: www.ons.gov.uk/ons/dcp171778_362910.pdf.

ONS (2018). Living longer: How our population is changing and why it matters Available at: https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/ageing/articles/livinglongerhowourpopulationischangingandwhyitmatters/2018-08-13.

ONS (2020). Population estimates for the UK, England and Wales, Scotland and Northern Ireland: Mid-2019 Available at: https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates/bulletins/annualmidyearpopulationestimates/latest.

Peng, Q., & Iwaki, S. (2020). Visual attention of young and older drivers in takeover tasks of highly automated driving. In *International conference on human-computer interaction* (pp. 210–221). Cham: Springer.

Persson, D. (1993). The elderly driver: Deciding when to stop. *The Gerontologist, 33*(1), 88–91.

Radlmayr, J., Gold, C., Lorenz, L., Farid, M., & Bengler, K. (2014). How traffic situations and non-driving related tasks affect the take-over quality in highly automated driving. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 58*, 2063–2067.

Raitanen, T., Törmäkangas, T., Mollenkopf, H., & Marcellini, F. (2003). Why do older drivers reduce driving? Findings from three European countries. *Transportation Research part F: Traffic Psychology and Behaviour, 6*(2), 81–95.

Rakotonirainy, A., Steinhardt, D., Delhomme, P., Darvell, M., & Schramm, A. (2012). Older drivers' crashes in Queensland, Australia. *Accident Analysis & Prevention, 48*, 423–429.

Regev, S., Rolison, J. J., & Moutari, S. (2018). Crash risk by driver age, gender, and time of day using a new exposure methodology. *Journal of Safety Research, 66*, 131–140.

Rodríguez-Aranda, C., Waterloo, K., Sparr, S., & Sundet, K. (2006). Age-related psychomotor slowing as an important component of verbal fluency. *Journal of Neurology, 253*(11), 1414.

Russell, R. M., Rasmussen, H., & Lichtenstein, A. H. (1999). Modified food guide pyramid for people over seventy years of age. *The Journal of Nutrition, 129*(3), 751–753.

SAE (2014) SAE taxonomy and definitions for terms related to on-road motor vehicle automated driving systems. [Online]. Available at: https://saemobilus.sae.org/content/j3016_201609 (Accessed: August 2018).

Santoni, G., Angleman, S., Welmer, A. K., Mangialasche, F., Marengoni, A., & Fratiglioni, L. (2015). Age-related variation in health status after age 60. *PLoS ONE, 10*(3) e0120077.

Schoene, D., Wu, S. M. S., Mikolaizak, A. S., Menant, J. C., Smith, S. T., Delbaere, K., & Lord, S. R. (2013). Discriminative ability and predictive validity of the timed Up and Go test in identifying older people who fall: Systematic review and meta-analysis. *Journal of the American Geriatrics Society, 61*(2), 202–208.

Shanmugaratnam, S., Kass, S. J., & Arruda, J. E. (2010). Age differences in cognitive and psychomotor abilities and simulated driving. *Accident Analysis & Prevention, 42*(3), 802–808.

Shergold, I., Lyons, G., & Hubers, C. (2015). Future mobility in an ageing society–Where are we heading? *Journal of Transport & Health, 2*(1), 86–94.

Siren, A., & Meng, A. (2013). Older drivers' self-assessed driving skills, driving-related stress and self-regulation in traffic. *Transportation Research Part F: Traffic Psychology and Behaviour, 17*, 88–97.

Stevens, A. (2000). Safety of driver interaction with in-vehicle information systems. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 214*(6), 639–644.

Stevens, A., Quimby, A., Board, A., Kersloot, T. and Burns, P. (2002) Design guidelines for safety of in-vehicle information systems. Project report PA3721/01. TRL Limited.

Su, F., & Bell, M. G. (2013). Travel differences by gender for older people in London. *Research in Transportation Economics, 34*(1), 35–38.

Sun, Q. C., Xia, J. C., Foster, J., Falkmer, T., & Lee, H. (2018). Driving manoeuvre during lane maintenance in older adults: Associations with neuropsychological scores. *Transportation Research Part F: Traffic Psychology and Behaviour, 53*, 117–129.

UN (2017) World population ageing 2017 highlights. [Online]. Available at: https://www.un.org/en/development/desa/population/publications/pdf/ageing/WPA2017_Highlights.pdf.

Van Asselen, M., & Ridderinkhof, K. R. (2000). Shift costs of predictable and unexpected set shifting in young and older adults. *Psychologica Belgica, 40*(4), 259–273.

van der Horst, R., & Hogema, J. (1993). *The 6th ICTCT workshop: Safety evaluation of traffic systems: Traffic conflicts and other measures*. Salzburg, Austrian: University of Lund.

Vaportzis, E., Georgiou-Karistianis, N., & Stout, J. C. (2013). Dual task performance in normal aging: A comparison of choice reaction time tasks. *PLoS ONE, 8*(3) e60265.

Vaportzis, E., Giatsi Clausen, M., & Gow, A. J. (2017). Older adults perceptions of technology and barriers to interacting with tablet computers: A focus group study. *Frontiers in Psychology, 8*, 1687.

WHO (2016) Definition of an older or elderly person. Available at: http://www.who.int/healthinfo/survey/ageingdefnolder/en/ (Accessed: October 2016).

WHO (2018). Ageing and health Available at: https://www.who.int/news-room/fact-sheets/detail/ageing-and-health.

Wu, Y., Kihara, K., Hasegawa, K., Takeda, Y., Sato, T., Akamatsu, M., & Kitazaki, S. (2020). Age-related differences in effects of non-driving related tasks on takeover performance in automated driving. *Journal of Safety Research, 72*, 231–238.

Yang, Y., Bender, A. R., & Raz, N. (2015). Age related differences in reaction time components and diffusion properties of normal-appearing white matter in healthy adults. *Neuropsychologia, 66*, 246–258.
Young, M. S., & Bunce, D. (2011). (2011) 'Driving into the sunset: Supporting cognitive functioning in older drivers'. *Journal of Aging Research*.
Zhang, B., de Winter, J., Varotto, S., Happee, R., & Martens, M. (2019). Determinants of take-over time from automated driving: A meta-analysis of 129 studies. *Transportation Research Part F: Traffic Psychology and Behaviour, 64*, 285–307.
Zhang, B., Wilschut, E. S., Willemsen, D. M., & Martens, M. H. (2019). Transitions to manual control from highly automated driving in non-critical truck platooning scenarios. *Transportation Research Part F: Traffic Psychology and Behaviour, 64*, 84–97.